Testing the W -exchange mechanism with two-body baryonic B decays

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ABSTRACT: The role of W -exchange diagrams in baryonic B decays is poorly understood, and often taken as insignificant and neglected. We show that charmful two-body baryonic $B \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$ decays provide a good test-bed for the study of the W -exchange topology, whose contribution is found to be non-negligible; here $\mathbf{B}_c$ is an anti-triplet or a sextet charmed baryon, and $\bar{\mathbf{B}}'$ an octet charmless (anti-)baryon. In particular, we calculate that $\mathcal{B}(\bar{B}^0 \rightarrow \Sigma_c^+ \bar{p}) = (2.9_{-0.9}^{+0.8}) \times 10^{-6}$ in good agreement with the experimental upper bound. Its cousin $\bar{B}_s^0$ mode, $\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{p}$, is a purely W -exchange decay, hence is naturally suited for the study of the role of the W -exchange topology. We predict $\mathcal{B}(\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{p}) = (0.8 \pm 0.3) \times 10^{-6}$, a relatively large branching ratio to be tested with a future measurement by the LHCb collaboration. Other predictions, such as $\mathcal{B}(\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Sigma}^-) = (1.1 \pm 0.4) \times 10^{-5}$, can be tested with future Belle II measurements.

KEYWORDS: B physics, Branching fraction, Flavor physics, Rare decay, Hadron-Hadron scattering (experiments)

ARXIV EPRINT: [1906.01805](https://arxiv.org/abs/1906.01805)

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1 Introduction

Decays of B mesons to multi-body baryonic final states, such as $B \rightarrow \mathbf{B}\bar{\mathbf{B}}'M$ and $\mathbf{B}\bar{\mathbf{B}}'MM'$, where $\mathbf{B}$ (M) represents a baryon (meson), have been richly studied. Their branching ratios are typically at the level of 10^{-6} [1]. These relatively large branching ratios are due to the fact that the baryon-pair production tends to occur in the threshold region of $m_{\mathbf{B}\bar{\mathbf{B}}'} \simeq m_{\mathbf{B}} + m_{\bar{\mathbf{B}}'}$, where the threshold effect with a sharply raising peak can enhance the branching ratio [2–5]. On the other hand, without the recoiled meson(s) to carry away the large energy release, the two-body $B \rightarrow \mathbf{B}\bar{\mathbf{B}}'$ decays proceed at the m_B scale, several GeV away from the threshold region, resulting in the suppression of their decay rates [6, 7]. So far, only three charmless modes have been seen experimentally: $\bar{B}^0 \rightarrow p\bar{p}$ ($\mathcal{B} \simeq \mathcal{O}(10^{-8})$) and $B^- \rightarrow \Lambda^{(*)}\bar{p}$ ($\mathcal{B} \simeq \mathcal{O}(10^{-7})$), with $\Lambda^* \equiv \Lambda(1520)$ [8–10].

The tree-level dominated $B \rightarrow \mathbf{B}\bar{\mathbf{B}}'$ decays can proceed through the W -exchange, emission and annihilation diagrams, depicted in figures 1(a,b,c), respectively. However, the W -exchange (annihilation) process is regarded as helicity suppressed [11, 12], and hence neglected in theoretical studies [13–18]. Moreover, one also neglects the penguin-level gluon-exchange (annihilation) contributions, which leads to $\mathcal{B}(\bar{B}_s^0 \rightarrow p\bar{p}) \simeq 0$ [17]. Consequently, the observation of the $\bar{B}_s^0 \rightarrow p\bar{p}$ decay would provide valuable information on whether contributions from the exchange (annihilation) processes play a significant role. The smallness of the current upper bound on its branching ratio, $\mathcal{B}(\bar{B}_s^0 \rightarrow p\bar{p}) < 1.5 \times 10^{-8}$ [8], indicates an experimentally difficult decay mode to study the role of exchange (annihilation) diagrams.

On the other hand, experimental data show that $\mathcal{B}(B \rightarrow \mathbf{B}_c\bar{\mathbf{B}}') \simeq (10^2 - 10^3)\mathcal{B}(B \rightarrow \mathbf{B}\bar{\mathbf{B}}')$, where $\mathbf{B}_c$ denotes a charmed baryon [1]. With significantly larger decay rates, charmed two-body baryonic B decays offer an interesting and suitable environment in which to study and test the role of the W -exchange (annihilation) mechanism. The set of measured $B \rightarrow \mathbf{B}_c\bar{\mathbf{B}}'$ branching ratios is nevertheless scarce [1, 19, 20]:

$$\begin{aligned}
\mathcal{B}(\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p}) &= (1.54 \pm 0.18) \times 10^{-5}, \\
\mathcal{B}(\bar{B}^0 \rightarrow \Sigma_c^+ \bar{p}) &< 2.4 \times 10^{-5}, \\
\mathcal{B}(B^- \rightarrow \Sigma_c^0 \bar{p}) &= (2.9 \pm 0.7) \times 10^{-5}.
\end{aligned} \tag{1.1}$$

Figure 1. Feynman diagrams for the $B \rightarrow \mathbf{B}_{(c)} \bar{\mathbf{B}}'$ decays, where (a,c) depict the W -exchange and annihilation processes, respectively, and (b) depicts the W -emission process, with $q = (u, d, s)$ for $B_q \equiv (\bar{B}^0, B^-, \bar{B}_s^0)$.

As in the case of the charmless final states considered above, the $B \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$ decays can proceed through both the W -exchange and W -emission diagrams. Again, theoretical studies regard the W -exchange diagram as helicity-suppressed, which is in analogy with the leptonic $B \rightarrow \ell \bar{\nu}_\ell$ decays, and take the W -emission diagram as the dominant contribution [13, 14, 18, 21, 22]. For clarification, we present the amplitudes of $B \rightarrow \ell \bar{\nu}_\ell$ and $B \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$ with W -exchange contribution in figure 1a as

$$\begin{aligned} \mathcal{A}(B \rightarrow \ell \bar{\nu}_\ell) &\propto m_\ell \bar{u}(1 + \gamma_5)v, \\ \mathcal{A}(B \rightarrow \mathbf{B}_c \bar{\mathbf{B}}') &\propto m_c \langle \mathbf{B}_c \bar{\mathbf{B}}' | \bar{c}(1 + \gamma_5)q | 0 \rangle, \end{aligned} \quad (1.2)$$

where $\mathcal{A}(B \rightarrow \mathbf{B}_c \bar{\mathbf{B}}')$ by equation of motion is presented as a reduced form with the quark mass m_c [23]. In eq. (1.2), the small m_ℓ , with $\ell = (e, \mu)$, is responsible for the helicity suppression in $B \rightarrow \ell \bar{\nu}_\ell$. Nonetheless, $m_c \sim 1.3 \text{ GeV}$ [1] in $\mathcal{A}(B \rightarrow \mathbf{B}_c \bar{\mathbf{B}}')$ is clearly helicity allowed, indicating that neglecting its contribution may not be a valid assumption to make. For completeness, we note that the theoretical studies in refs. [23–26] also considered the exchange and annihilation contributions in $B \rightarrow \mathbf{B} \bar{\mathbf{B}}'$ and $D_s^+ \rightarrow p \bar{n}$.

We therefore propose the study of the family of charmful two-body baryonic $B \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$ decays to improve our knowledge of the role of W -exchange diagrams in B decays to baryonic final states. Since modes such as $\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Sigma}^-$ and $\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{p}$ can only proceed via the W -exchange diagram, measurements of their branching ratios are direct tests of the W -exchange mechanism.

$\bar{B}^0 \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$	Amplitudes	$\bar{B}^0 \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$	Amplitudes
$\Lambda_c^+ \bar{p}, \Lambda_c^+ \bar{\Delta}^-$	$\mathcal{A}_{\text{ex}} + \mathcal{A}_{\text{em}}$	$\Sigma_c^{++} \bar{\Delta}^{--}$	$\mathcal{A}_{\text{ex}}$
$\Xi_c^+ \bar{\Sigma}^-$	$\mathcal{A}_{\text{ex}}$	$\Sigma_c^+ \bar{p}, \Sigma_c^+ \bar{\Delta}^-$	$\mathcal{A}_{\text{ex}} + \mathcal{A}_{\text{em}}$
$\Xi_c^0 \bar{\Lambda}, \Xi_c^0 \bar{\Sigma}^0$	$\mathcal{A}_{\text{ex}} + \mathcal{A}_{\text{em}}$	$\Sigma_c^0 \bar{n}, \Sigma_c^0 \bar{\Delta}^0$	$\mathcal{A}_{\text{ex}} + \mathcal{A}_{\text{em}}$
		$\Xi_c'^+ \bar{\Sigma}^-$	$\mathcal{A}_{\text{ex}}$
		$\Xi_c'^0 \bar{\Lambda}, \Xi_c'^0 \bar{\Sigma}^0$	$\mathcal{A}_{\text{ex}} + \mathcal{A}_{\text{em}}$
		$\Omega_c^0 \bar{\Xi}^0$	$\mathcal{A}_{\text{ex}}$
$\bar{B}_s^0 \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$	Amplitudes	$\bar{B}_s^0 \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$	Amplitudes
$\Lambda_c^+ \bar{p}, \Lambda_c^+ \bar{\Delta}^-$	$\mathcal{A}_{\text{ex}}$	$\Sigma_c^{++} \bar{\Delta}^{--}$	$\mathcal{A}_{\text{ex}}$
$\Xi_c^+ \bar{\Sigma}^-$	$\mathcal{A}_{\text{ex}} + \mathcal{A}_{\text{em}}$	$\Sigma_c^+ \bar{p}, \Sigma_c^+ \bar{\Delta}^-$	$\mathcal{A}_{\text{ex}}$
$\Xi_c^0 \bar{\Lambda}, \Xi_c^0 \bar{\Sigma}^0$	$\mathcal{A}_{\text{ex}} + \mathcal{A}_{\text{em}}$	$\Sigma_c^0 \bar{n}, \Sigma_c^0 \bar{\Delta}^0$	$\mathcal{A}_{\text{ex}}$
		$\Xi_c'^+ \bar{\Sigma}^-$	$\mathcal{A}_{\text{ex}} + \mathcal{A}_{\text{em}}$
		$\Xi_c'^0 \bar{\Lambda}, \Xi_c'^0 \bar{\Sigma}^0$	$\mathcal{A}_{\text{ex}} + \mathcal{A}_{\text{em}}$
		$\Omega_c^0 \bar{\Xi}^0$	$\mathcal{A}_{\text{ex}} + \mathcal{A}_{\text{em}}$

Table 1. Classification for $B \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$ decays, where $\mathcal{A}_{\text{ex}}$ and $\mathcal{A}_{\text{em}}$ denote the amplitudes through the W -exchange and W -emission diagrams, respectively.

2 Formalism

Besides the W -emission ($\mathcal{A}_{\text{em}}$) amplitudes studied elsewhere [18, 21, 22], we consider the often neglected W -exchange ($\mathcal{A}_{\text{ex}}$) amplitudes for the charmful two-body baryonic $\bar{B}_{(s)}^0 \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$ decays, where $\mathbf{B}_c$ denotes the anti-triplet and the sextet charmed baryon states, $(\Xi_c^{+,0}, \Lambda_c^+)$ and $(\Sigma_c^{++,+,0}, \Xi_c'^{+,0}, \Omega_c^0)$, respectively, and $\bar{\mathbf{B}}'$ an octet charmless (anti-)baryon. The decays with the decuplet charmless (anti-)baryons are excluded from the calculations in this paper due to the lack of the corresponding timelike baryon form factors.

We show in table 1 the amplitudes involved in the interested $\bar{B}_{(s)}^0 \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$ modes. The decay rate of modes that can only occur through the W -exchange diagram would be vanishingly small by construction if the importance of these diagrams was to be insignificant:

$$\begin{aligned} \mathcal{B}(\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Sigma}^-, \Sigma_c^{++} \bar{\Delta}^{--}, \Xi_c'^+ \bar{\Sigma}^-, \Omega_c^0 \bar{\Xi}^0) &= 0, \\ \mathcal{B}(\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{p}, \Lambda_c^+ \bar{\Delta}^-, \Sigma_c^{++} \bar{\Delta}^{--}, \Sigma_c^+ \bar{p}, \Sigma_c^+ \bar{\Delta}^-, \Sigma_c^0 \bar{n}, \Sigma_c^0 \bar{\Delta}^0) &= 0. \end{aligned} \quad (2.1)$$

None of these relations has yet been verified experimentally.

The relevant part of the Hamiltonian for the $\bar{B}_{(s)}^0 \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$ decays has the following form [27]:

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_{q=d,s} V_{cb} V_{uq}^* \left[c_1^{\text{eff}}(\bar{q}u)(\bar{c}b) + c_2^{\text{eff}}(\bar{c}u)(\bar{q}b) \right], \quad (2.2)$$

where G_F is the Fermi constant, V_{ij} stand for the CKM matrix elements, and $(\bar{q}_1 q_2)_{V-A} \equiv \bar{q}_1 \gamma^\mu (1 - \gamma_5) q_2$. In the factorization approach, the W -exchange amplitude of $\bar{B}_{(s)}^0 \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$

is given by [21, 23]

$$\mathcal{A}(\bar{B}_{(s)}^0 \rightarrow \mathbf{B}_c \bar{\mathbf{B}}') = \frac{G_F}{\sqrt{2}} a_2 V_{cb} V_{uq}^* \langle \mathbf{B}_c \bar{\mathbf{B}}' | (\bar{c}u)_{V-A} | 0 \rangle \langle 0 | (\bar{q}b)_{V-A} | \bar{B}_{(s)}^0 \rangle, \quad (2.3)$$

where $q = d(s)$ for $\bar{B}_{(s)}^0$, and $a_2 = c_2^{\text{eff}} + c_1^{\text{eff}}/N_c$ consists of the effective Wilson coefficients $(c_1^{\text{eff}}, c_2^{\text{eff}}) = (1.168, -0.365)$ and the color number N_c .

The matrix elements in eq. (2.3) are defined as [1, 22]

$$\begin{aligned} \langle 0 | \bar{q} \gamma^\mu (1 - \gamma_5) b | B \rangle &= -i f_B q^\mu, \\ \langle \mathbf{B}_c \bar{\mathbf{B}}' | \bar{c} \gamma^\mu u | 0 \rangle &= \bar{u} \left[f_1 \gamma^\mu + \frac{i f_2}{m_{\mathbf{B}_c} + m_{\bar{\mathbf{B}}'}} \sigma^{\mu\nu} q_\nu + \frac{f_3}{m_{\mathbf{B}_c} + m_{\bar{\mathbf{B}}'}} q^\mu \right] v, \\ \langle \mathbf{B}_c \bar{\mathbf{B}}' | \bar{c} \gamma^\mu \gamma_5 u | 0 \rangle &= \bar{u} \left[g_1 \gamma^\mu + \frac{i g_2}{m_{\mathbf{B}_c} + m_{\bar{\mathbf{B}}'}} \sigma^{\mu\nu} q_\nu + \frac{g_3}{m_{\mathbf{B}_c} + m_{\bar{\mathbf{B}}'}} q^\mu \right] \gamma_5 v, \end{aligned} \quad (2.4)$$

where f_B is the B meson decay constant, $q^\mu = (p_{\mathbf{B}_c} + p_{\bar{\mathbf{B}}'})^\mu$ the momentum transfer, and f_i and g_i ($i = 1, 2, 3$) are the timelike baryonic ($0 \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$) form factors. The decay amplitude of $B \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$ in the general form is written as

$$\mathcal{A}(B \rightarrow \mathbf{B}_c \bar{\mathbf{B}}') = \bar{u} (A_S + A_P \gamma_5) v, \quad (2.5)$$

with $A_{S,P}$ standing for the (S, P) -wave amplitudes. By only receiving the W -exchange contributions in eq. (2.3), the $A_{S,P}$ are given by

$$A_S = C_S m_- \left[f_1 + \left(\frac{m_B^2}{m_+ m_-} \right) f_3 \right], \quad A_P = C_P m_+ \left[g_1 + \left(\frac{m_B^2}{m_+^2} \right) g_3 \right], \quad (2.6)$$

where $C_{S,P} = \mp i G_F a_2 V_{cb} V_{uq}^* f_B / \sqrt{2}$, $m_\pm = m_{\mathbf{B}_c} \pm m_{\bar{\mathbf{B}}'}$, and (f_2, g_2) vanish due to the contraction of $\sigma_{\mu\nu} q^\mu q^\nu = 0$. We use the timelike baryonic form factors with the light-front quark model [28], which have been widely applied to the b and c -hadron decays [29–35]. In the light-front frame, since the momentum transfer q^μ is presented as $q^+ = q^0 + q^3 = 0$, it simply indicates the non-contributions from (f_3, g_3) as in the case of the $B \rightarrow M$ transition [34, 35]. This is in accordance with lattice QCD calculations, where the derivations of $(f_3, g_3) \propto (f_1, g_1)/t$ show the suppression in the spacelike region [36], even though the corrections beyond leading order have been considered. Therefore, (f_3, g_3) are often neglected in the literature [22, 37].

By the double-pole parameterization, $F(t) \equiv (f_1(t), g_1(t))$ is presented as [37]

$$F(t) = \frac{F(0)}{1 - a(t/m_B^2) + b(t^2/m_B^4)}, \quad (2.7)$$

with $t \equiv q^2$. The $\text{SU}(3)$ flavor symmetry can relate $F(0)$ in the different decays, given by

$$(C_f^{\mathbf{B}_c \bar{\mathbf{B}}'}, C_g^{\mathbf{B}_c \bar{\mathbf{B}}'}) = \xi (C_f^{\Lambda_c^+ \bar{p}}, C_g^{\Lambda_c^+ \bar{p}}), \quad (C_f^{\mathbf{B}_c \bar{\mathbf{B}}'}, C_g^{\mathbf{B}_c \bar{\mathbf{B}}'}) = \zeta (C_f^{\Sigma_c^+ \bar{p}}, C_g^{\Sigma_c^+ \bar{p}}), \quad (2.8)$$

with $(C_f, C_g) \equiv (f_1(0), g_1(0))$ and $|\xi|$ ($|\zeta|$) for the anti-triplet (sextet) charmed baryons listed in table 2. We compute the branching ratios from the decay-rate equation for two-

$\bar{\mathbf{3}}_c \otimes \mathbf{8}$	$ \xi $	$\mathbf{6}_c \otimes \mathbf{8}$	$ \zeta $
$\Lambda_c^+ \bar{p}$	1	$\Sigma_c^+ \bar{p}$	1
$\Xi_c^+ \bar{\Sigma}^-$	1	$\Sigma_c^0 \bar{n}$	$\sqrt{2}$
$\Xi_c^0 \bar{\Lambda}$	$\frac{1}{\sqrt{6}}$	$\Xi_c'^+ \bar{\Sigma}^-$	1
$\Xi_c^0 \bar{\Sigma}^0$	$\frac{1}{\sqrt{2}}$	$\Xi_c'^0 \bar{\Sigma}^0$	$\frac{1}{\sqrt{2}}$
		$\Xi_c'^0 \bar{\Lambda}$	$\sqrt{\frac{3}{2}}$
		$\Omega_c^0 \bar{\Xi}^0$	$\sqrt{2}$

Table 2. The relations between different timelike baryon form factors. The $\bar{\mathbf{3}}_c$ and $\mathbf{6}_c$ denote the anti-triplet and the sextet charmed baryons, respectively, and the $\mathbf{8}$ denotes the octet charmless baryons.

body decays, given by [1]

$$\mathcal{B}(B \rightarrow \mathbf{B}_c \bar{\mathbf{B}}') = \frac{|\vec{p}_{\mathbf{B}_c}| \tau_B}{8\pi m_B^2} |\mathcal{A}(B \rightarrow \mathbf{B}_c \bar{\mathbf{B}}')|^2, \quad (2.9)$$

$$|\vec{p}_{\mathbf{B}_c}| = \frac{\sqrt{(m_B^2 - m_+^2)(m_B^2 - m_-^2)}}{2m_B},$$

where τ_B denotes the B meson lifetime.

3 Numerical analysis

In the numerical analysis, we adopt the Wolfenstein parameterization for the CKM matrix elements, given by [1]

$$(V_{cb}, V_{ud}, V_{us}) = (A\lambda^2, 1 - \lambda^2/2, \lambda), \quad (3.1)$$

where $\lambda = 0.22453 \pm 0.00044$ and $A = 0.836 \pm 0.015$, together with the B meson decay constants $(f_B, f_{B_s}) = (0.19, 0.23) \text{ GeV}$ [1]. The light-front quark model provides

$$\begin{aligned} (C_f^{\Lambda_c^+ \bar{p}}, a, b) &= (0.41_{-0.09}^{+0.07}, 0.75, 0.45), \\ (C_g^{\Lambda_c^+ \bar{p}}, a, b) &= (0.37_{-0.08}^{+0.07}, 0.90, 0.50), \\ (C_f^{\Sigma_c^+ \bar{p}}, a, b) &= (-0.25 \pm 0.04, 0.70, 0.40), \\ (C_g^{\Sigma_c^+ \bar{p}}, a, b) &= (-0.21 \pm 0.04, 0.84, 0.52), \end{aligned} \quad (3.2)$$

where $C_{f,g}^{\Lambda_c^+ \bar{p}}$ and $C_{f,g}^{\Sigma_c^+ \bar{p}}$ relate the different decays with $(|\xi|, |\zeta|)$ in table 2.

By considering the non-factorizable W -emission contributions only, the pole model relates $B^- \rightarrow \Sigma_c^0 \bar{p}$ and $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p}$ with the same sets of strong coupling constants [12, 22]. We follow ref. [22] to re-extract the strong coupling constants with the most current data of $\mathcal{B}(B^- \rightarrow \Sigma_c^0 \bar{p}) = 2.9 \times 10^{-5}$ [1], which leads to $\mathcal{B}(\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p}) = 0.4 \times 10^{-5}$ in comparison with the data of $(1.55 \pm 0.18) \times 10^{-5}$. In order to explain the data, the often neglected

Decay modes	$\mathcal{B} \times 10^5$	Data	Decay modes	$\mathcal{B} \times 10^6$	Data
$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p}$	$1.0^{+0.4}_{-0.3}$	1.54 ± 0.18 [1]	$\bar{B}^0 \rightarrow \Sigma_c^+ \bar{p}$	$2.9^{+0.8}_{-0.9}$	< 24 [1]
$\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Sigma}^-$	1.1 ± 0.4		$\bar{B}^0 \rightarrow \Sigma_c^0 \bar{n}$	$5.8^{+1.5}_{-1.8}$	
$\bar{B}^0 \rightarrow \Xi_c^0 \bar{\Sigma}^0$	0.6 ± 0.2		$\bar{B}^0 \rightarrow \Xi_c'^+ \bar{\Sigma}^-$	$3.1^{+0.9}_{-1.0}$	
$\bar{B}^0 \rightarrow \Xi_c^0 \bar{\Lambda}$	0.2 ± 0.1		$\bar{B}^0 \rightarrow \Xi_c'^0 \bar{\Sigma}^0$	$1.6^{+0.4}_{-0.5}$	
			$\bar{B}^0 \rightarrow \Xi_c'^0 \bar{\Lambda}$	$4.6^{+1.3}_{-1.5}$	
			$\bar{B}^0 \rightarrow \Omega_c^0 \bar{\Xi}^0$	$6.4^{+1.8}_{-2.1}$	
Decay modes	$\mathcal{B} \times 10^6$		Decay modes	$\mathcal{B} \times 10^7$	
$\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{p}$	0.8 ± 0.3		$\bar{B}_s^0 \rightarrow \Sigma_c^+ \bar{p}$	$2.3^{+0.6}_{-0.7}$	
$\bar{B}_s^0 \rightarrow \Xi_c^+ \bar{\Sigma}^-$	0.9 ± 0.3		$\bar{B}_s^0 \rightarrow \Sigma_c^0 \bar{n}$	$4.5^{+1.1}_{-1.4}$	
$\bar{B}_s^0 \rightarrow \Xi_c^0 \bar{\Sigma}^0$	0.4 ± 0.2		$\bar{B}_s^0 \rightarrow \Xi_c'^+ \bar{\Sigma}^-$	$2.5^{+0.6}_{-0.8}$	
$\bar{B}_s^0 \rightarrow \Xi_c^0 \bar{\Lambda}$	0.2 ± 0.1		$\bar{B}_s^0 \rightarrow \Xi_c'^0 \bar{\Sigma}^0$	$1.2^{+0.3}_{-0.4}$	
			$\bar{B}_s^0 \rightarrow \Xi_c'^0 \bar{\Lambda}$	$3.6^{+0.9}_{-1.2}$	
			$\bar{B}_s^0 \rightarrow \Omega_c^0 \bar{\Xi}^0$	$5.1^{+1.4}_{-1.7}$	

Table 3. Branching ratios of the $\bar{B}_{(s)}^0 \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$ decays from the W -exchange diagrams.

W -exchange contribution to $\mathcal{B}(\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p})$ should be at the level of 10^{-5} . With $N_c = 2.9$ ($a_2 = 0.04$), we are able to get $\mathcal{B}(\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p}) = (1.0^{+0.4}_{-0.3}) \times 10^{-5}$ with the errors from the uncertainties of the form factors. In the generalized factorization, one allows N_c to shift from 2 to ∞ as an effective number to account for the non-factorizable strong interaction. Particularly, $N_c \simeq 3$ implies a mild correction [38]. Accordingly, we estimate the previously neglected W -exchange contributions to $\mathcal{B}(B \rightarrow \mathbf{B}_c \bar{\mathbf{B}}')$, given in table 3.

4 Discussions and conclusions

Several suppression factors have been proposed to support the neglecting of the W -exchange (annihilation) contributions. The first one is in analogy with the semileptonic $B \rightarrow \ell \bar{\nu}_\ell$ decays [12]. In fact, we obtain

$$\begin{aligned}
 \mathcal{B}(B \rightarrow \ell \bar{\nu}_\ell) &= \frac{G_F^2 m_{B\tau B}}{8\pi} |V_{ub}|^2 f_B^2 m_\ell^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2, \\
 \mathcal{B}(B \rightarrow \mathbf{B}_c \bar{\mathbf{B}}') &= \frac{G_F^2 |\vec{p}_{\mathbf{B}_c}| \tau_B}{8\pi} |a_2 V_{cb} V_{uq}^*|^2 f_B^2 m_+^2 \left[\mathcal{R}_m f_1^2 \left(1 - \frac{m_+^2}{m_B^2}\right) + g_1^2 \left(1 - \frac{m_-^2}{m_B^2}\right) \right], \quad (4.1)
 \end{aligned}$$

with $\mathcal{R}_m \equiv (m_-/m_+)^2$. While m_μ^2 is responsible for the helicity suppressed $\mathcal{B}(B^- \rightarrow \mu^- \bar{\nu}_\mu) \simeq 10^{-7}$ [39], $B \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$ with $m_+^2 = (m_{\mathbf{B}_c} + m_{\bar{\mathbf{B}}'})^2$ obviously allows for helicity-flip. The second one is the decay constant $f_B = 0.19 \text{ GeV}$ in eq. (4.1), regarded as small and suppressing the W -exchange contribution [40]. However, it is found that $\mathcal{B}(B^- \rightarrow \tau^- \bar{\nu}_\tau)$ with f_B can still be as large as $(1.09 \pm 0.24) \times 10^{-4}$ [1]. Besides, the ratio of $m_\mu^2/m_\tau^2 \sim$

$\mathcal{O}(10^{-3})$ implies the smallness of $\mathcal{B}(B^- \rightarrow \mu\bar{\nu}_\mu)/\mathcal{B}(B^- \rightarrow \tau\bar{\nu}_\tau) \sim \mathcal{O}(10^{-3})$. Hence, it is reasonable to infer that f_B cannot be the main cause of the suppression. Third, in the *charmless* $B \rightarrow \mathbf{B}\bar{\mathbf{B}}'$ decays, one of the suppression factors for $\mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}) \sim \mathcal{O}(10^{-8})$ comes from $(f_1, g_1) \propto (\alpha_s/t)^2$ with $t = m_B^2$, which corresponds to the hard gluons that transfer the energy of m_B [23, 41]. In the $B \rightarrow \mathbf{B}_c\bar{\mathbf{B}}'$ decays, however, (f_1, g_1) with a charmed baryon are not small at $t = m_B^2$, as shown in eqs. (2.7) and (3.2). Note that (f_1, g_1) in the timelike and spacelike regions can be associated with the crossing symmetry, and (f_1, g_1) with the light-front quark model agree with those in lattice QCD calculations [28, 36]. By contrast, $\mathcal{B}(\bar{B}^0 \rightarrow \Lambda_c^+\bar{p})$ was once calculated as small as 4.6×10^{-7} [42], taken as the another theoretical support for the neglect of the W -exchange diagram [12, 22]. However, the estimation was done with the baryonic form factors in the dipole form of $F(0)/(1 - t/m_{D^*}^2)$ adopted from the $\Lambda_c^+ \rightarrow p$ transition [42], such that the momentum transfer at m_B exceeds the D^* meson pole, causing the suppression, whereas the validity of the D^* meson pole has never been tested in the timelike region. Besides, $F(0)$ was not clearly given, due to the lack of the studies on the quark and QCD models at that time.

With the W -exchange contributions, we obtain

$$\begin{aligned}\mathcal{B}(\bar{B}^0 \rightarrow \Sigma_c^+\bar{p}) &= (2.9_{-0.9}^{+0.8}) \times 10^{-6}, \\ \mathcal{B}(\bar{B}^0 \rightarrow \Sigma_c^0\bar{n}) &= (5.8_{-1.8}^{+1.5}) \times 10^{-6},\end{aligned}\tag{4.2}$$

where $\mathcal{B}(\bar{B}^0 \rightarrow \Sigma_c^+\bar{p})$ is consistent with the current data in eq. (1.1). In particular, $\mathcal{B}(\bar{B}^0 \rightarrow \Sigma_c^0\bar{n})$ is predicted to be ten times larger than the pole model calculation [22]. On the other hand, by only considering the W -emission contribution, the pQCD approach gives that $\mathcal{B}(\bar{B}^0 \rightarrow \Lambda_c^+\bar{p}) = (2.3 - 5.1) \times 10^{-5}$ [18], which is more than 4 standard deviations away from the measured central value. It is interesting to know if the pQCD approach would overestimate $\mathcal{B}(B^- \rightarrow \Sigma_c^0\bar{p})$ as well. One way of comparing the W -emission and exchange contributions is by studying decays other than $\bar{B}^0 \rightarrow \Lambda_c^+\bar{p}, \Sigma_c^+\bar{p}$, which receive contributions from both $\mathcal{A}_{\text{ex}}$ and $\mathcal{A}_{\text{em}}$. By taking $\mathcal{A}_{\text{ex}}$ as the primary contribution, we predict that

$$\begin{aligned}\mathcal{B}(\bar{B}^0 \rightarrow \Xi_c^0\bar{\Sigma}^0, \Xi_c^0\bar{\Lambda}) &= (0.6 \pm 0.2, 0.2 \pm 0.1) \times 10^{-5}, \\ \mathcal{B}(\bar{B}_s^0 \rightarrow \Xi_c^0\bar{\Sigma}^0, \Xi_c^0\bar{\Lambda}) &= \mathcal{R}_{B_s} \times \mathcal{B}(\bar{B}^0 \rightarrow \Xi_c^0\bar{\Sigma}^0, \Xi_c^0\bar{\Lambda}),\end{aligned}\tag{4.3}$$

with $\mathcal{R}_{B_s} \equiv |(V_{us}f_{B_s})/(V_{ud}f_B)|^2 = 0.075$. In future measurements the deviation of $\mathcal{R}_{B_s}$ from the theoretical prediction can be used to evaluate the size of $\mathcal{A}_{\text{em}}$ in the decays. Being pure W -exchange processes, $\bar{B}^0 \rightarrow \Xi_c^+\bar{\Sigma}^-, \Xi_c'^+\bar{\Sigma}^-, \Omega_c^0\bar{\Xi}^0$ and $\bar{B}_s^0 \rightarrow \Sigma_c^0\bar{n}, \Lambda_c^+\bar{p}, \Sigma_c^+\bar{p}$ can be excellent probes for the examination of the W -exchange mechanism. Therefore, we predict that

$$\begin{aligned}\mathcal{B}(\bar{B}^0 \rightarrow \Xi_c^+\bar{\Sigma}^-) &= (1.1 \pm 0.4) \times 10^{-5}, \\ \mathcal{B}(\bar{B}_s^0 \rightarrow \Lambda_c^+\bar{p}) &= (0.8 \pm 0.3) \times 10^{-6}, \\ \mathcal{B}(\bar{B}^0 \rightarrow \Xi_c'^+\bar{\Sigma}^-, \Omega_c^0\bar{\Xi}^0) &= (3.1_{-1.0}^{+0.9}, 6.4_{-2.1}^{+1.8}) \times 10^{-6},\end{aligned}\tag{4.4}$$

which are all within the capability of the current B factories.

In summary, we have studied the charmful two-body baryonic $B_{(s)}^0 \rightarrow \mathbf{B}_c \bar{\mathbf{B}}'$ decays, with $\mathbf{B}_c = (\Xi_c^{+,0}, \Lambda_c^+)$ or $(\Sigma_c^{++,+,0}, \Xi_c'^{+,0}, \Omega_c^0)$. We have found that the often neglected W -exchange contribution is in fact not negligible. Particularly, we obtain that $\mathcal{B}(\bar{B}^0 \rightarrow \Sigma_c^+ \bar{p}) = (2.9_{-0.9}^{+0.8}) \times 10^{-6}$, agreeing with the current data. For decays that only proceed via the W -exchange diagram, we predict $\mathcal{B}(\bar{B}_s^0 \rightarrow \Lambda_c^+ \bar{p}) = (0.8 \pm 0.3) \times 10^{-6}$ and $\mathcal{B}(\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Sigma}^-) = (1.1 \pm 0.4) \times 10^{-5}$, which provide an excellent window for the LHCb and Belle II experiments to look into the long-ignored W -exchange mechanism.

Acknowledgments

This work was supported in part by National Science Foundation of China (11675030) and U. S. National Science Foundation award ACI-1450319.

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